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14. ABSTRACT

The subject of our project supported by the AFOSR is the dynamics of intense charged beams focused by magnetic fields. There are several applications for this kind system, ranging from microwaves to controlled nuclear fusion.

Our group is currently composed by two coordinator faculties (F.B. Rizzato and R. Pakter), two collaborators (Prof. Yan Levin and Dr. Antônio Endler), and several graduate students, some of which having finished their doctoral and master thesis in the field of Beam Physics and Vacuum Electronics during the grant period: Jorge Soares (PhD), Karen Fiuza (PhD), Roger Pizzato (PhD), Wilson Simeoni (Master), Tarcisio Teles (Master) Alexandre Bonatto (Master), Everton Graneman, Luciano Martins.

We were mostly interested in the study of relaxation processes and halo formation of high-intensity beams in vacuum tubes. Some of our research effort also contemplates microwave coherence in nonlinear media and wake field electron acceleration.

15. SUBJECT TERMS
Beam Physics, Particle Acceleration, Beam Transport, Beam Instabilities, Nonlinear Dynamics, Wave Coherence.

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• Objectives

Our program involved the study of nonlinear properties of intense beams of charged particles transported under the action of magnetic focusing fields. This kind of system finds a very wide range of applications, such as particle acceleration, RF generation, communication technologies, and controlled nuclear fusion.

We have been dedicating a considerable amount of attention to the analysis of emittance growth in beams initially far from equilibrium. Emittance growth is related to particles ejected from the beam core and is a potentially limiting factor for beam performance. Recently papers by our group show that beam inhomogeneities are frequently behind particle ejection, either acting as the central mechanism, like in wave-breaking coasting beams, or as a precursor of associated mechanisms, like in the case of nonlinear resonances. In any case, particles acquire very large velocities and may cause heavy beam losses.

Other recent lines of investigation involve dynamics of beams in elliptical geometries, which is of relevance for modern microwave devices, and the study of asymptotic distribution functions for initially mismatched beams. In this latter case, techniques inspired by Lynden-Bell methods (Ref. [5] below) enable to look at emittance growth as a kind of violent relaxation dynamics. Wave coherence arising from nonlinear media, also a relevant issue for microwave devices, is a topic of interest as well.

• Research Effort

Our group works with theoretical tools and self-consistent numerical simulations, having achieved a series of results in the area. We have investigated emittance growth in mismatched beams both when the beam density is homogeneous and inhomogeneous. In the former case we created a technique to incorporate emittance growth in a low-dimensional model for the dynamics, and in the latter, we performed a series of calculations and simulations whereby beam relaxation via wave-breaking leading to particle jets, and subsequent emittance growth were all observed. More recently, modeling techniques based on Lagrangian fluid coordinates allowed us to accurately estimate the relaxed asymptotic states of wave-breaking beams. All these results have been published in refereed journals and presented in conferences in the area. We have also been involved with the analysis of asymmetrical and elliptical beams propagating in circular conducting apertures. This is of interest in the design of microwave valves where the elliptical geometry is necessary to achieve high gain regimes in amplification of electromagnetic signal seeds. A variational calculation combined with image charge methods allowed us to predict with accuracy the beam shape as it enters the conducting tube.

We have also investigated with a little more care the problem of relaxation in mismatched homogeneous beams. Both in theoretical and computational approaches, violent relaxation was seen in the transport of matched and mismatched beams.

The group is also investigating wave coherence in nonlinear media. Nonlinear effects can actually help coherence rather than suppressing it. The idea is inspired in the phase-locking mechanism of nonlinear classical oscillators. Large nonlinear resonance islands trap orbits in their interior and force these orbits to synchronize in a coherent fashion. Our idea, following former works of Peter Robinson and Peter Drysdale of Univ. of Sydney, Australia, was to apply the concept to electromagnetic radiation in nonlinear media like dense beams, for instance. And the results really indicate that fields above a certain threshold induce large levels of coherence in the dynamics.

• Group Members, Flow and Activity During the Grant Period

Our group is composed by two coordinators, Prof. Felipe Barbedo Rizzato and Prof. Renato Pakter, by one faculty collaborator, Prof. Yan Levin, by two posdocs, Dr. Antônio Endler and Dr. Roger Pizzato Nunes, and five graduate students, Tarciso Teles, Alexandre Bonatto, Wilson Simeoni Jr., Everton Graneman Souza and Luciano Martins. Two former students, Roger Pizzato Nunes and Karen Fiuza recently obtained their doctorate titles. Most of the personnel is working with intense beams and vacuum electronics, while alternative acceleration schemes, like beat wave accelerators, form the interest of Alexandre Bonatto, who recently obtained his Master degree.

• Most Recent Publications and Conferences

(i) We list the most recent publications and achievements of our group:

1. LEVIN, Y. ; PAKTER, R. ; TELES, T. N. . Collisionless relaxation in nonneutral plasmas. Physical Review Letters, v. 100, p. 040604, 2008.

2. OLIVEIRA, G. I. ; F.B. RIZZATO . Coherence and incoherence in extended broad band triplet interaction. Physical Review E - Statistical Physics, Plasmas, Fluids and Related Interdisciplinary Topics, v. 77, p. 016607-1-016607-6, 2008.

3. NUNES, R. P. ; PAKTER, R. ; Rizzato, F. B. . An analytical model to determine equilibrium quantities of azimuthally symmetric and mismatched charged particle beams under linear focusing. Journal of Applied Physics, v. 104, p. 013302, 2008.

4. Levin, Yan ; Pakter, Renato ; Rizzato, Felipe B. . Collisionless relaxation in gravitational systems: From violent relaxation to gravothermal collapse. Physical Review. E, Statistical, Nonlinear and Soft Matter Physics, v. 78, p. 021130, 2008.

5. PAKTER, R. ; LEVIN, Y. ; F.B. RIZZATO . Image Effects on the Transport of Intense Nonaxisymmetric Charged Beams. Applied Physics Letters, v. 91, p. 251503, 2007.

(ii) in addition, as mentioned earlier, we presented our results at the 2008 EPAC, Genova Italy, at the 2008 AFOSR Workshop on Nonlinear Optics, Dayton, OH, and at the ICPP 2008, Fukuoka, Japan.

• US Collaborations

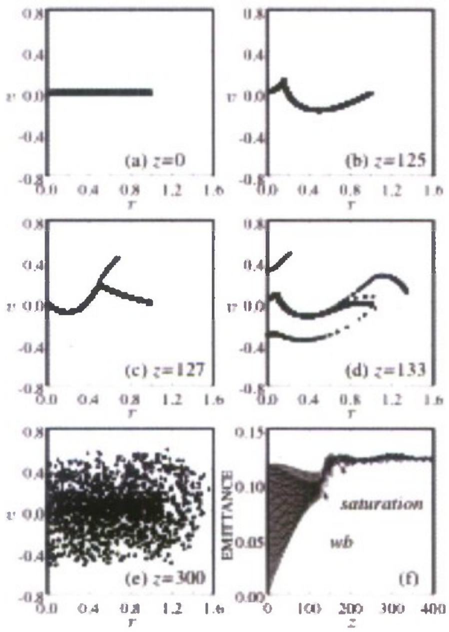
We maintain active collaboration with Dr. Chiping Chen (and his group) from the MIT Plasma Science and Fusion Center.

• Description of the Current Group Sub-Projects and Achievements Sponsored by AFOSR Grant

Wave breaking, particle jets, and emittance growth in intense inhomogeneous charged beams

In this particular sub-project, we investigate the process of wave breaking in space-charge dominated beams, $r_b^2 \approx K/\kappa$ (if one looks at the envelope equation above, this latter relation means that emittance effects are at least initially unimportant) with inhomogeneous profiles across the beam transverse section. Wave breaking always takes place as long as some inhomogeneity is present. Unlike other cases where breaking occurs only when thresholds on field or oscillatory amplitudes are exceeded, in the present case the beam is transversally unstable and breaking is inevitable if the validity conditions for the model hold. Wave breaking produces particle jets that can be responsible for the appearance of kinetic effects in the system. Kinetic effects make the connection between coordinates and velocities multi-valued (as shall be seen in the next figure) which breaks down the simple fluid picture for the whole dynamics. The presence of kinetic effects and jets is somewhat equivalent to heating, whereby coherent fluctuations of density are gradually converted into microscopic degrees of freedom associated to beam emittance. Wave breaking is not the only way to relax initially mismatched beams, as it has been shown that oscillations of mismatched envelopes can be damped by Gluckstern's (Gluckstern, Phys. Rev. Letts. 1997) resonances. However, inhomogeneities are much harder to suppress than envelope mismatches, which would leave us with the former in various experimental situations (Lund et al, N.I.M.A 2005). These would decay according to what has been exposed here.

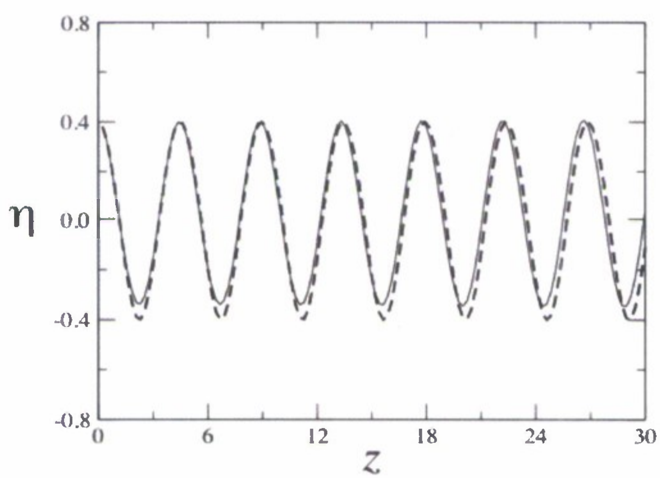
Several instances of transverse beam dynamics in the next figure. Panel (a) represents the initial



state where all particles have vanishing velocity. In panel (b) the system is depicted for a "time" z (=s) where a cusp is about to form in phase-space. The third panel (c) panel shows what happens when particles are ejected off wave fronts in a wave-breaking fashion. The bulk still has moderate velocites, but the ejected particles acquire larger speeds. The fourth panel accompanies the ejected particles and the fifth panel shows the beam aspect asymptotic times where one reaches the stationary plateaus in the emittance curve shown in the sixth panel. *wb* in panel (f) denotes the point where wave-breaking takes place.

More recently we have created a low-dimensional model to estimate core oscillations and resulting halo formation. The model is based on average Lagrangian techniques aided by test-particle analysis. With the average Langrangian we determine the dominant oscillatory frequency of the beam core, and placing test particles under the action of the core bounding curves delimiting the halo phase-space are determined.

Calling η the factor measuring thc inhomogeneities of the beam, we werc able to model the fully simulated model in terms of our low-dimensional model as below; full lines are simulations and dotted lines, the model. Thesc good agreement allowed us to accurately estimate the halo size and density (with further help of conserved quantities).

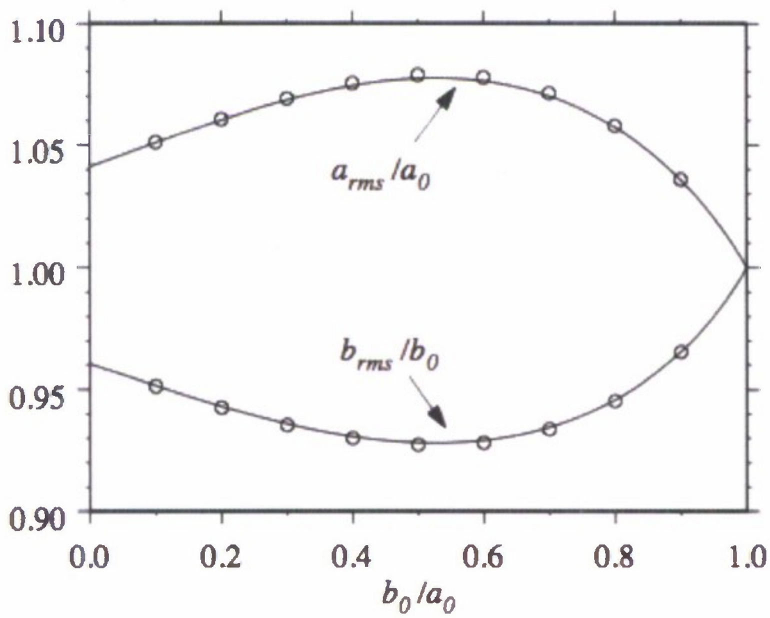


<u>Image Effects on the Transport of Intense Nonaxisymmetric Charged Beams</u>

In this topic we havc investigated the cffects of a conducting pipe on the equilibrium of intense nonaxisymmetric beams. First, we analyzed the image effects of a cylindrical conducting pipc on a continuous beam with elliptical symmetry and derived an cxact expression for the electrostatic potential.

Using a variational method, we then calculated the equilibrium beam shape and its charge distribution. It was found that the presence of a pipe does not alter the effective beam cross sectional area. This suggested that the variational equations possess an underlying hidden symmetry.

Using an adiabatic construction we were able to prove that despite the nonlinear forces exerted by the induced charges, the intense particle beams preserve a uniform equilibrium density, as long as the focusing forces are linear. Furthermore, the cross sectional area of the beam remains the same as in the absence of a conductor.

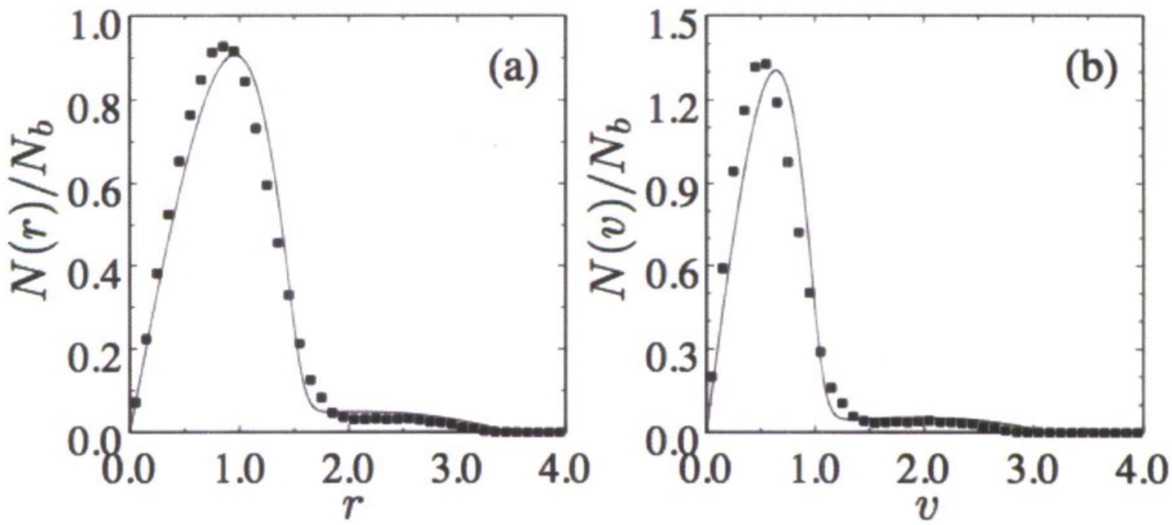


In the above figure we depict the equilibrium beam dimensions inside the conducting pipe, a_{rms} and b_{rms}, as functions of the respective values assumed in the absence of the pipe. Curves represent result of our analytical variational approach, and circles, the corresponding simulations. The pipe is 1.2 times larger than the a_0 axis and naturally has no influences in the symmetric case when $a_0=b_0$. Agreement between numerics and analytical estimates is excellent. An interesting result here is that even for highly asymmetrical beams, the effect of the pipe is at most very moderate. This fortunately means that beam geometrical calculations can be made regardless of the pipe.

These findings should have important practical implications for the design of intense beam transport channels.

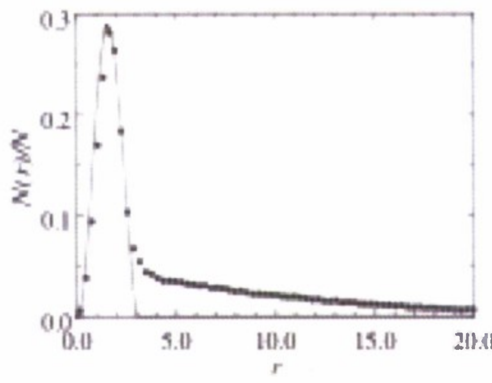
Collisionless relaxation in non-neutral plasmas

In this sub-project we are studying confined one component plasmas of charges interacting by unscreened Coulomb potential. Unlike normal gases with short range forces, non-neutral plasmas do not evolve to the state of thermodynamic equilibrium. Instead collisionless relaxation culminates in a stationary state in which the detailed balance is violated. Using a combination of non-equilibrium statistical mechanics and the theory of parametric resonances it is, nevertheless, possible to a priory predict the distribution functions for the final stationary state. Unlike the normal thermodynamic equilibrium, this state, however, explicitly depends on the initial distribution of particle velocities and positions.



(a) Position (in units of K/κz, as defined earlier) and (b) velocity (in units of √K) distributions. Points are the result of N-particle dynamics simulations. Solid curves are the theoretical predictions obtained using the distribution function of Eq. (10). Dashed curves are the predictions of the violent relaxation theory based on Ref. [5]. The figure demonstrates that for oscillating beams, mixing is inefficient and violent relaxation theory does not apply. The initial distribution is uniform with r= 1.0.

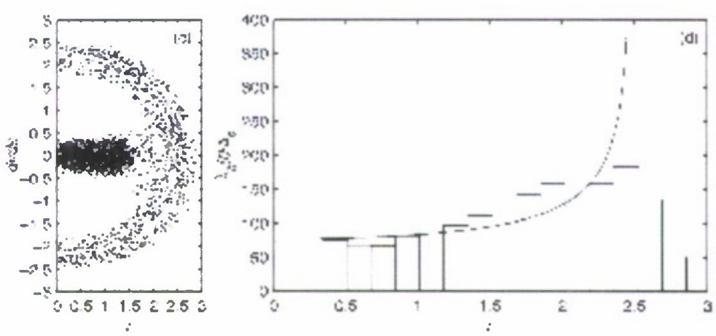
The same techniques were employed in a recent investigation of gravitational systems. The physics is similar since particles exhibit long range Coulomb-like interaction. It is true that the charge changes sign, but the relaxed states depend more on the conservation of phase-space volume than on anything else. Therefore, one expects similar relaxed behavior. This is confirmed with the figure below, where we again show spatial density versus radius for a spherical symmetry.



The figure shows a "cold" peak at small radial coordinates and a hot halo for largers distance. The cold peak is perfectly described by a cold Fermi-Dirac distribution exactly as in the case of charged particles.

More on homogeneous beams

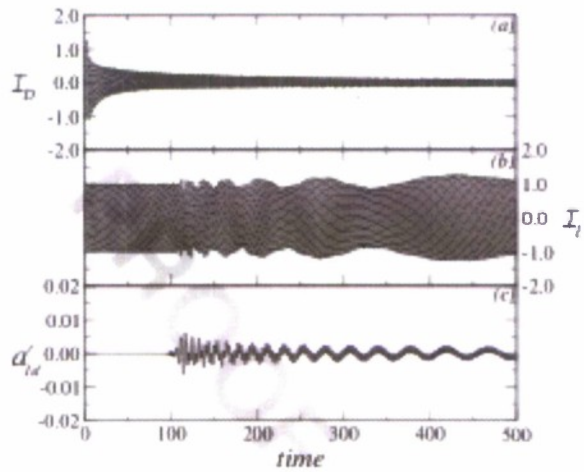
Further results were obtained in the case of mismatched homogeneous beams and published in the Journal of Applied Physics, **104**, 013302 (2008). We have corrected our halo modeling, thus obtaining improved agreement between estimates and simulations, as shown in the following figures where halo density for the situation depicted on the left, is compared with simulation results on the right.



Nonlinear coherence in optical beams

We study the transition from coherent to incoherent dynamics in a nonlinear triplet of broadband combs of waves. Expanding the analysis of previous works, we investigate what happens when the band of available modes is much larger than that of the initial narrower combs within which the nonlinear interaction is not subjected to selection rules involving wave momenta. Here selection rules are present and active, and we examine how and when coherence can be defined.

In the figure we show the importance of nonlinearity. While for the upper panel amplitudes are small, and no phase-locking or coherence can be seen in the average field, in the middle panel, amplitudes are large, phase-locking is present, and the average observable field goes undamped. Small fluctuations in this latter case are attributed to precursor-like signals which appears when the border line modes of the wave combs are strongly excited. Nevertheless coherence does not decay if wave amplitudes are large.



• Numerical Techniques

In all cases what has to be done is the integration of several thousands of particles interacting via Coulomb fields. Two ways are devised to perform the integration: (i) Green functions techniques and (ii) mean field techniques such as particles-in-cell and Gaussian models for spherical symmetric distributions.

In the former case (i) we first obtain the field generated by each particle, including boundary effects like those provided by conducting walls. Electric fields are then calculated and the acceleration of each particle is then obtained. To emulate the effects of an infinite number of particles, a soft core potential is used to remove singular effects arising from the close encounter of groups of particles. This model quite effective but time consuming since it does not deal with mean fields which would be more convenient for a assembly of many particles.

The latter mean field models indicated in item (ii) takes into account the statistical properties of this large number of particles. Particle-in-cell is effective when emittance is not too small, which poses a small restriction on its use. Gauss's law involves direct integration of Poission's equation for spherical symmetric distributions and assumes one single particle under the mean field produced by all others. It is very effective, but, as mentioned, can be used only under the restriction of azimuthally symmetric distributions.

As for the time advance of the equations governing the particle orbits, Runge-Kutta algorithms with automatically varying time steps prove to be quite satisfactory.

Our codes are fully available for any users.

• Conclusions and Acknowledgements

During these three years of support by the AFOSR/SOARD grant, we maintained our productivity on the area of waves and beams. Several papers were published and presented at various major conferences, and a number of students obtained their PhD and Master degrees. All in all, we considered as very positive the group performance, and acknowledge the Scientific Office and the South America division for their continuing help, interest, and extreme friendliness.